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Frequency Tripler with Anti-serial Schottky Diodes

M. Krach, J. Freyer, and M. Claassen

Abstract—In this paper a new type of frequency-multiplier from 70 GHz to 210 GHz [1] is presented which combines the advantages of a varactor with symmetrical capacitance-voltage characteristic and the low leakage current of Schottky diodes. The varactor structure consists of two inhomogeneously doped Schottky diodes in anti-serial connection which are quasi-monolithically integrated into a microstrip circuit on quartz. A theoretical description of the Schottky diode tripler is given and first experimental results are presented which show an rf-output power of 2 mW at 210 GHz.

I. INTRODUCTION

Frequency multipliers use non-linear devices to generate harmonics from fundamental oscillators. They are applied as practical rf-power sources above 200 GHz since power generation of fundamental oscillators normally is too low at these frequencies. The single Schottky diode is the most commonly used device though its application e. g. for frequency triplers is more complex as compared to varactors with symmetric capacitance-voltage characteristics, as the single-barrier varactor [2, 3]. In this case, the rf-circuit can be less complicated since no bias and idler circuits are necessary. However, the disadvantage of the single-barrier varactor is the relatively high leakage current which limits the rf-modulation.

In this paper, we present a new type of varactor structure with two inhomogeneously doped anti-serial Schottky diodes exhibiting a symmetric capacitance-voltage characteristic with relatively low leakage currents. The devices and the rf-circuit are fabricated quasi-monolithically on quartz substrate and are tested as frequency-multiplier from 70 GHz to 210 GHz.

II. NONLINEAR DEVICE

Bradley et al. [4] have shown that two anti-serial Schottky diodes with constant doping cannot be applied as varactors. This is due to the fact that with changing total charge, the

space-charge region of the reverse biased diode increases by the same amount by which the space-charge region of the forward diode is reduced. Thus, no non-linear total capacitance-voltage characteristic appears. This is, however, not valid if the doping concentration in the depletion layer is non-uniform. Then the space-charge region variations of the forward and the reverse diode differ from each other resulting in a variable total capacitance with respect to the total voltage. Due to opposite self-biasing, both diodes operate in a range of low conduction current [5].

The layer sequence of the applied Schottky diodes is schematically shown in Fig. 1. A large barrier height is realised by the use of an undoped 10 nm thick AlGaAs layer below the Schottky contact. The remaining depletion zone is split up into two layers with stepwise constant doping concentration followed by a highly n-doped zone for ohmic contact.

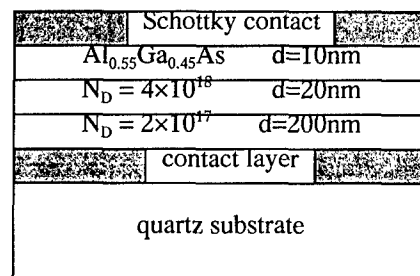


Fig. 1: Schematic layer sequence of the investigated Schottky diodes

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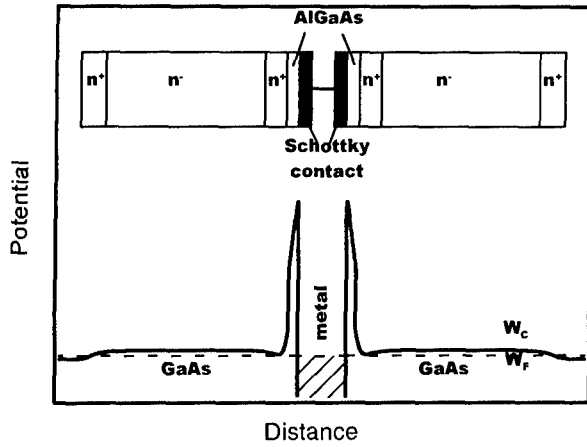


Fig. 2: Schematic layer sequence and band edge diagram of the anti-serial Schottky diodes

The symmetric varactor is realised by an anti-series connection of the two diodes with common Schottky contact schematically shown in Fig. 2.

III. SIMULATION

To determine the device properties, a simulation programme was developed which considers space-charge fields, thermionic field emission, tunnelling and impact ionisation. Capacitance-voltage and current-voltage characteristics of a single Schottky diode are calculated as follows:

Energy-band diagrams in the direction perpendicular to the layers of the structure are calculated by solving Poisson's equation self-consistently while requiring overall charge neutrality across the structure and satisfying the following boundary conditions:

1. The semiconductor properties are bulk-like.
2. With zero bias, the Fermi level remains constant throughout the entire structure and under applied bias V_a , the Fermi levels on the left and right hand side of the Schottky barrier must differ by eV_a (applied voltage).

Due to high charge densities, in some regions the Fermi level can be energetically higher than the conduction band edge. Therefore, the Fermi distribution function has to be applied to calculate the space-charge density.

The energy-band diagrams for different applied voltages may then be used to calculate the I-V characteristics of the Schottky diodes. Thermionic emission of electrons over the barrier and tunnelling of electrons through the barrier is computed using the model of Tsu and Esaki [6], in which the current density in the z direction is given by:

$$J_T = \frac{em^* k_B T}{2\pi\hbar^3} \cdot \int_0^\infty dE T(E) \ln \left(\frac{1 + e^{(E_F - E)/k_B T}}{1 + e^{(E_F - E - eV_a)/k_B T}} \right), \quad (1)$$

where m^* is the effective mass for electrons in the conduction band, e the elementary charge, E_F the Fermi level in the metal, V_a the applied voltage and E the kinetic energy of the electron due to the motion in the z direction. The transmission probability $T(E)$ is computed using WKB approximation [7]. For high voltages also impact ionisation has to be taken into account. This additional contribution to the conduction current can be implemented by the use of an impact ionisation coefficient [8].

The capacitance versus voltage behaviour of the device is calculated from the change of electric field with applied voltage:

$$C = \epsilon_r \epsilon_0 A \frac{dF}{dU}, \quad (2)$$

where F is the electric field and A the area of the diode.

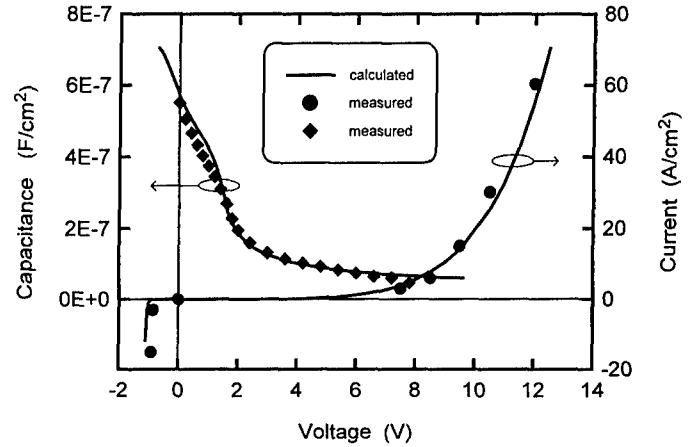


Fig. 3: Experimental and theoretical capacitance-voltage and current-voltage characteristics of a single Schottky diode (see Fig.1)

The capacitance-voltage and current-voltage characteristics of the investigated structure are depicted in Fig. 3 for a single Schottky diode showing good agreement of measured and simulated data.

The dynamic capacitance voltage characteristic of the anti-series connection of two diodes, which determines the efficiency of the tripler, can be calculated from the capacitance-voltage characteristic of a single Schottky diode. For this purpose the charge-voltage characteristic of a single diode is calculated by integrating the capacitance-voltage characteristic of the device. With this charge-voltage characteristic and the charge displacement due to the self-biasing, which is rf-voltage amplitude dependent, the total charge-voltage characteristic of the anti-series connection of two diodes can be computed. The differentiation of the total charge-voltage characteristic provides the rf-capacitance voltage characteristic of the multiplier device [5]. As an example, the resulting total rf-capacitance-voltage characteristic of two anti-serial

Schottky diodes with doping profile from Fig. 1 and characteristics from Fig. 3 is depicted in Fig. 4.

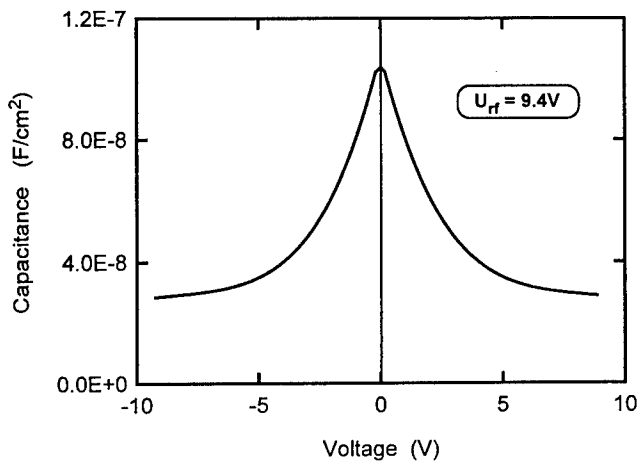


Fig. 4: Rf-capacitance-voltage characteristic of the symmetric varactor with two anti-serial Schottky diodes with a dopingprofile according to Fig. 1 and an rf-voltage of 9.4 V

The rf-voltage is 9.4 V in this case. It can be seen that the inhomogeneous doping profile in the depletion zone results in a strong non-linearity of the capacitance-voltage characteristic which enables application in frequency multipliers.

IV. RF-CIRCUIT

The tripler with the two devices was quasi-monolithically integrated into a microstrip tripler circuit on quartz substrate. The anti-serial Schottky diodes are connected in series via air-bridges between input and output circuit. The initial material is grown on GaAs substrate by MBE technique and after the removal of the substrate, the entire rf-circuit including the varactor is fabricated on quartz substrate using standard photoresist technology. The quartz chip with the rf-circuit, which consists of the nonlinear device, a low-pass filter, and input as well as output coupling, is placed into a split waveguide mount with two symmetrical halves. Details can be found elsewhere [9, 10]. Tuning of the tripler is obtained by backshorts at both input and output waveguide (see Fig. 5). The design of the whole circuit was carried out by the help of microwave analysis programmes (ADS, HFSS) [11].

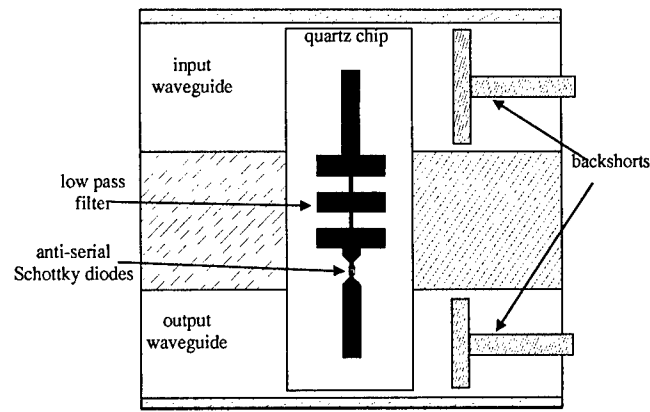


Fig. 5: Schematical view of the waveguide mount and quartz chip including the rf-circuit with quasi-monolithically integrated diodes

V. EXPERIMENTAL RESULTS

The current-voltage characteristic of the investigated Schottky diodes indicates relatively low leakage currents for reverse voltages up to 13 V. The diodes have a diameter of 10 μm and a series resistance of about 6 Ω . Tripler performance was tested at a fundamental frequency of 70 GHz. First experimental results achieved an rf-output power of 2 mW at 210 GHz with a flange to flange conversion efficiency of over 3 %. Up to this output level, saturation neither of efficiency nor of power has been observed. It should be noted that the structure of the diodes and the circuit are not yet optimised. Further work will focus on this field to increase the performance of the tripler.

VI. CONCLUSION

A new anti-series Schottky diode frequency tripler with an output frequency of 210 GHz, fabricated on quartz substrate, is reported. A theoretical description of the multiplier device as well as first experimental results are given. The rf-circuit with the nonlinear device was tested in a split full height waveguide mount. Considering the non-optimised structure for the Schottky diodes and the circuit, the achieved result of 2 mW output power is encouraging and shows the potential of this new tripler concept.

VII. ACKNOWLEDGEMENT

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